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Strain Rate Dependence of Polyurethane Foam Materials

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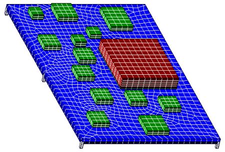
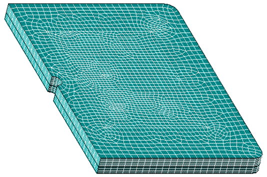
Introduction

- Foams are used to protect sensitive components, which may subject to impact, crush, tumble and shock
- Constitutive data of the mechanical behaviors of foams are needed to develop, characterize and validate large deformation foam models
- Variety of foams
  - Closed cell and open cell foams
  - Density (8 – 50 pcf)
  - Closed cell polyurethane foams

    FR3712 (General Plastics), **PMDI** and TufFoam foams (Sandia)

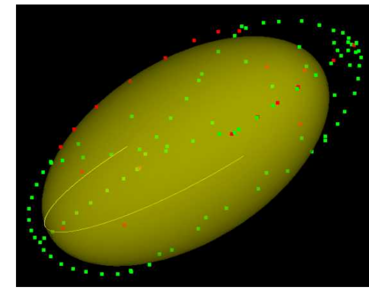




- Application environment for foam constitutive models
  - Large deformation
  - Strain rate (10^{-4} – 10^{3} s^{-1})
  - Temperature (-65 – 165 ^{o}F)

Foam Plasticity Model

for Closed Cell Polyurethane Foams



Yield Function

$$\varphi = \frac{\bar{\sigma}^2}{a^2} + \frac{p^2}{b^2} - 1.0$$

Effective Stress

$$\bar{\sigma} = \sqrt{\frac{3}{2}\mathbf{s} : \mathbf{s}}$$

Pressure

$$p = \frac{-1}{3}\boldsymbol{\sigma} : \mathbf{i}$$

Deviatoric Stress

$$\mathbf{s} = \boldsymbol{\sigma} + p\,\mathbf{i}$$

References:

- Deshpande, V.S. and Fleck, N.A. (2000), *J. Mech. Phys. Solids,* **48**, 1253-83.
- Zhang, J. et al (1998), *Int. J. Impact Engng*., 21, 369-386.
- Brannon, R.M. (2000), SAND2000-2696, Sandia National Labs.

Foam Plasticity Model

Flow Rule

$$\dot{\boldsymbol{\varepsilon}}^{p} = \dot{\lambda}\,\mathbf{g}$$

Associated Flow

$$\mathbf{g}_{\text{associated}} = \frac{\dfrac{\partial \varphi}{\partial \boldsymbol{\sigma}}}{\left|\dfrac{\partial \varphi}{\partial \boldsymbol{\sigma}}\right|} = \frac{\dfrac{3}{a^{2}}\mathbf{s} - \dfrac{2}{3b^{2}}p\,\mathbf{i}}{\left|\dfrac{3}{a^{2}}\mathbf{s} - \dfrac{2}{3b^{2}}p\,\mathbf{i}\right|}$$

Radial Flow

$$\mathbf{g}_{\text{radial}} = \frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|} = \frac{\boldsymbol{\sigma}}{\sqrt{\boldsymbol{\sigma}:\boldsymbol{\sigma}}}$$

Non-assoc. Flow

$$\mathbf{g} = (1-\beta)\,\mathbf{g}_{\text{associated}} + \beta\,\mathbf{g}_{\text{radial}}$$

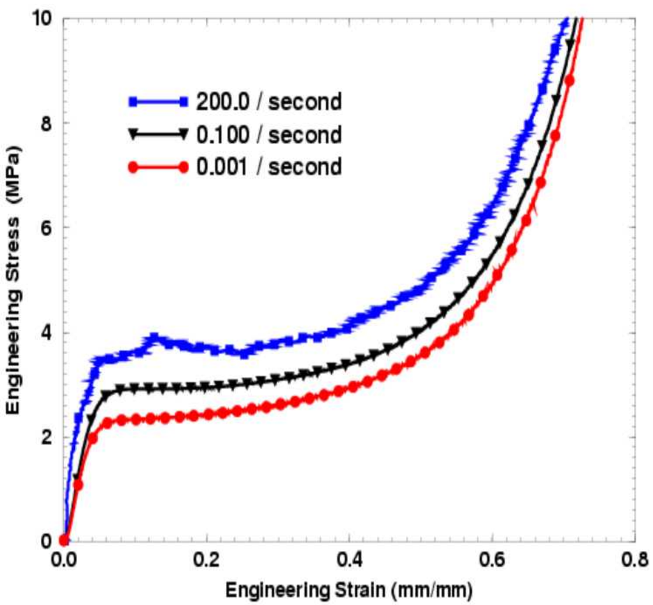
Evolution Equations

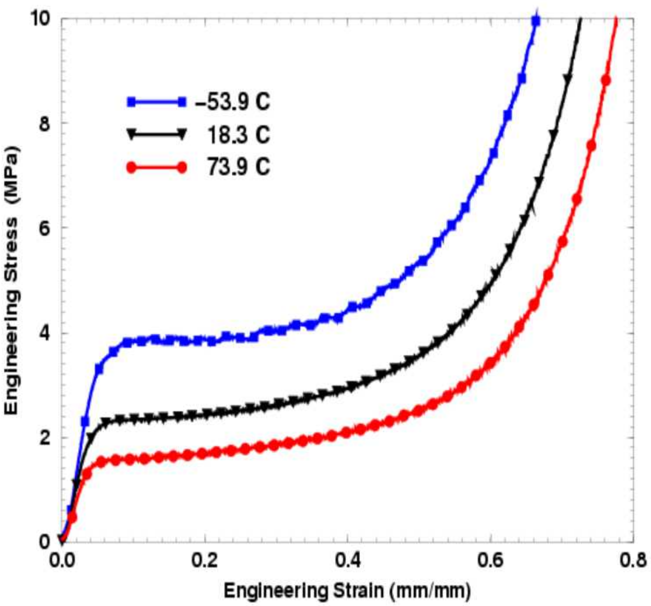
$$a = A0 + A1\,\phi^{A2}$$

$$b = B0 + B1\,\phi^{B2}$$

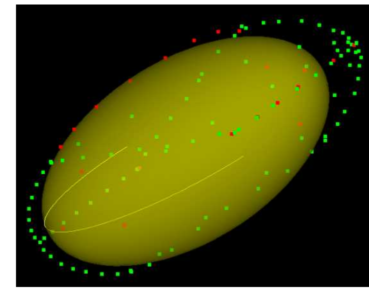
Experimental Observations

- Foam Plasticity Model is able to capture both the deviatoric and volumetric plasticity exhibited by polyurethane foams
- The model is not able to capture the significant effects that changes in strain rate and temperature have on the material response





Viscoplastic Model for Foam
Perzyna-type Formulation



Yield Function from Plasticity Model

$$\varphi = \frac{\bar{\sigma}^2}{a^2} + \frac{p^2}{b^2} - 1 = 0$$

Rewritten as Follows

$$\varphi = \sigma^* - a = 0$$

where

$$\sigma^* = \sqrt{\bar{\sigma}^2 + \frac{a^2}{b^2} p^2}$$

Inelastic Rate is Given by

$$\dot{\boldsymbol{\varepsilon}}^{vp} = \begin{cases} h(\theta) \left\langle \dfrac{\sigma^*}{a} - 1 \right\rangle^{n(\theta)} \mathbf{g} & \text{when } \dfrac{\sigma^*}{a} - 1 > 0 \\ \mathbf{0} & \text{when } \dfrac{\sigma^*}{a} - 1 \le 0 \end{cases}$$

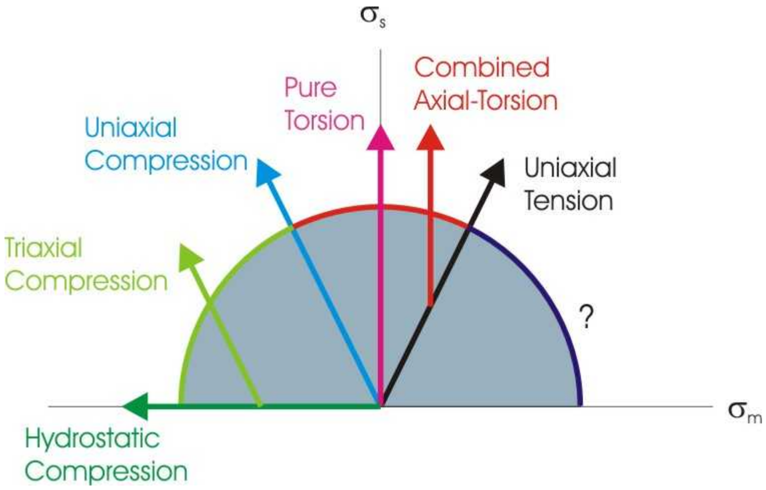
Non-associated Flow

$$\mathbf{g} = (1 - \beta)\, \mathbf{g}_{associated} + \beta\, \mathbf{g}_{radial}$$

Reference: M. Neilsen, W-Y Lu, W. Olsson, T. Hinnerichs, IMCHE2006-14551

Model Calibration

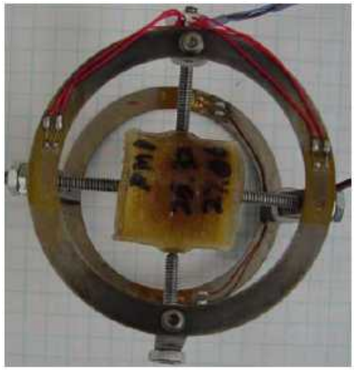
- Model parameters are estimated from the stress-strain curves of the uniaxial compression experiments and the strength-volume fraction responses of the hydrostatic experiments
- Rate and temperature effects are based on the results of uniaxial compression.

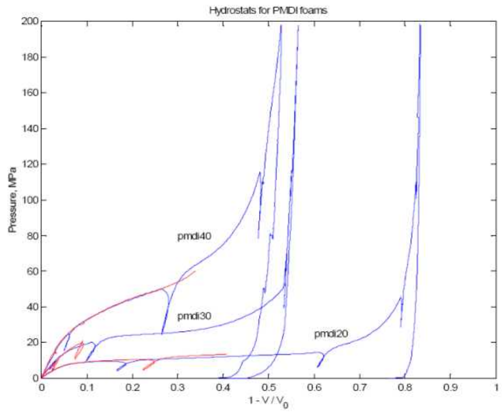


Hydrostatic Testing

Setup and Results

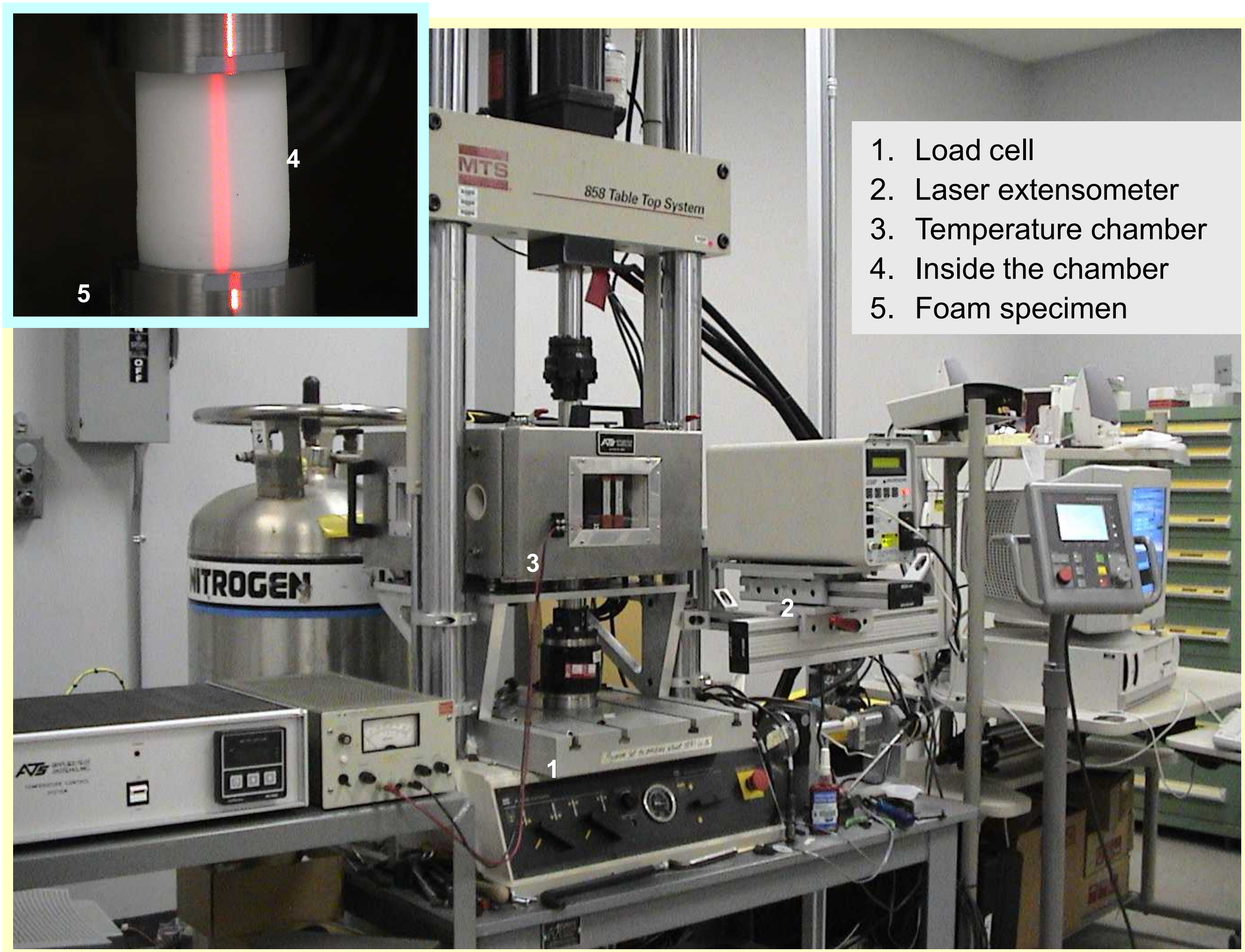
(Bill Olssen)





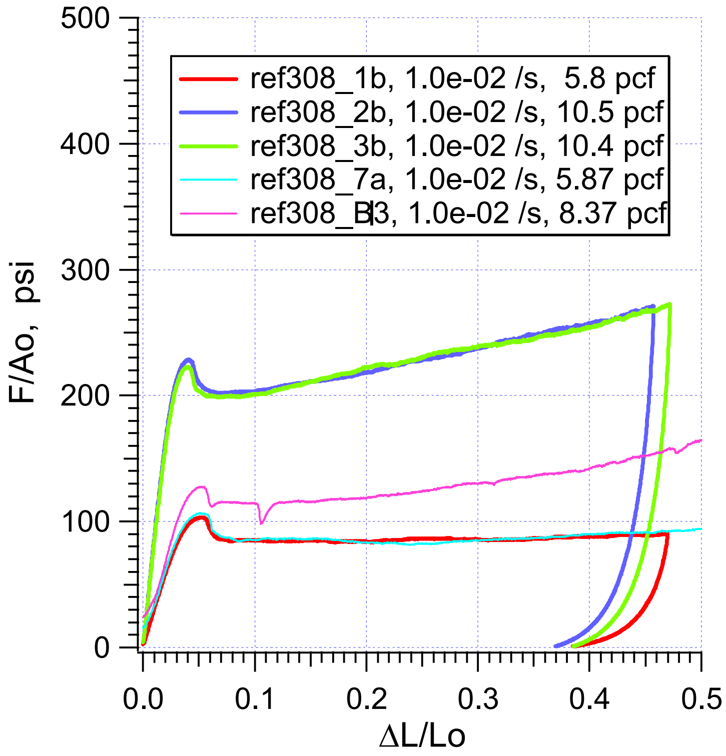
Low Strain Rate

Strain Rate < 10 /s



REF308 Compression at Ambient

Strain Rate: 1.0E-02



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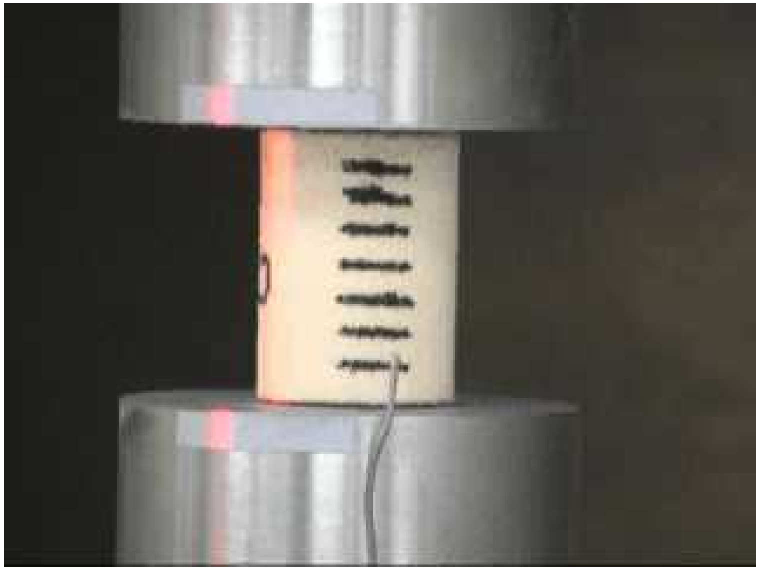


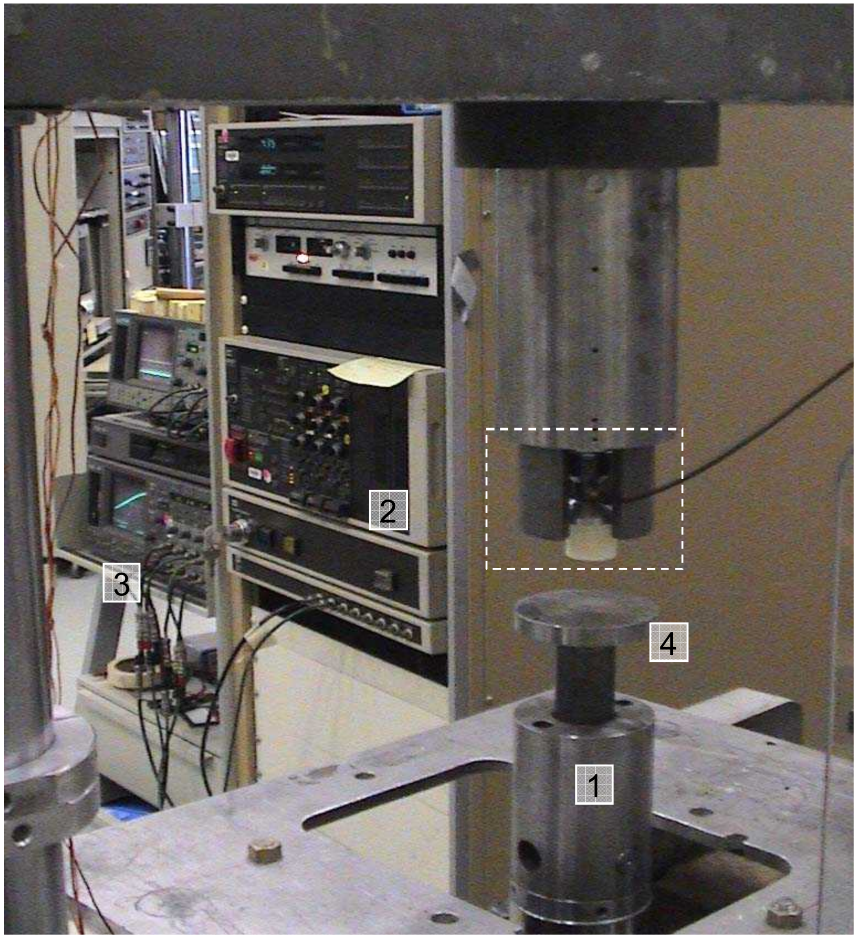
Click to play video

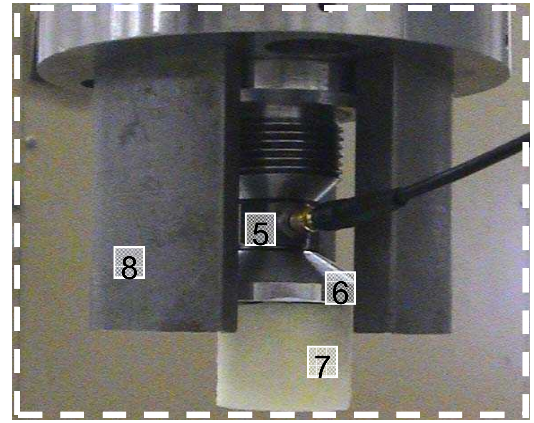
Record: 30 fps

Playback: 150 fps

Intermediate Strain Rate

10 /s < Strain Rate < 500 /s

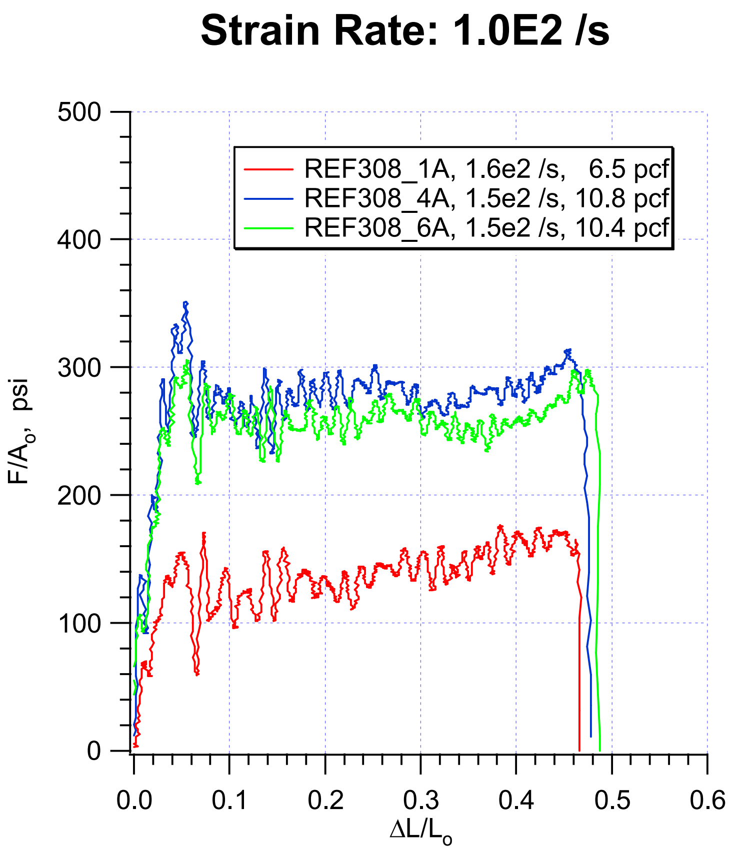


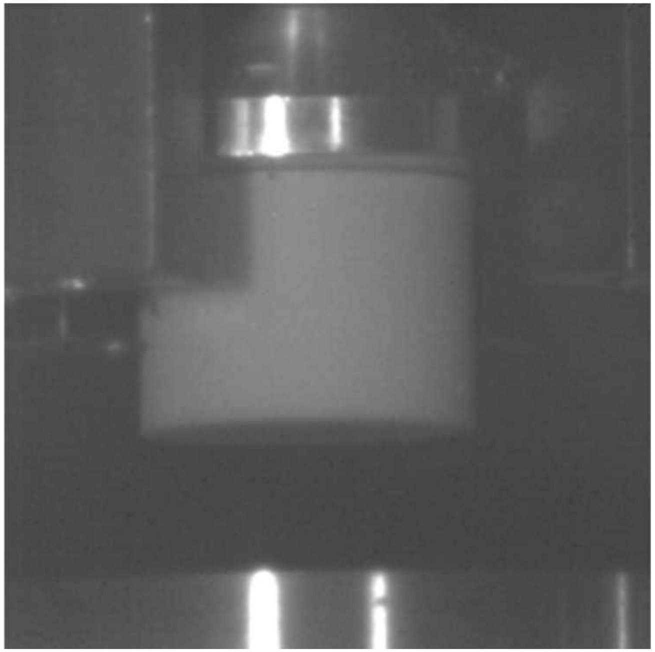


Experiment setup

1 shear-pin break-off fixture on the actuator,
2 customized MTS controller,
3 Nicolet data acquisition unit,
4 lower platen,
5 load cell,
6 upper platen,
7 foam specimen, and
8 maximum displacement gage block

REF308 Compression at Ambient



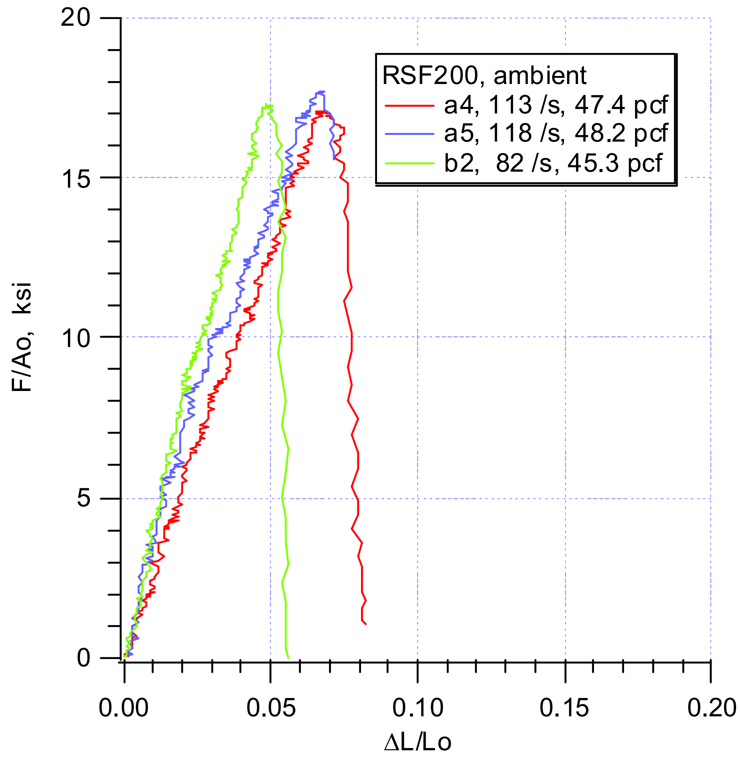


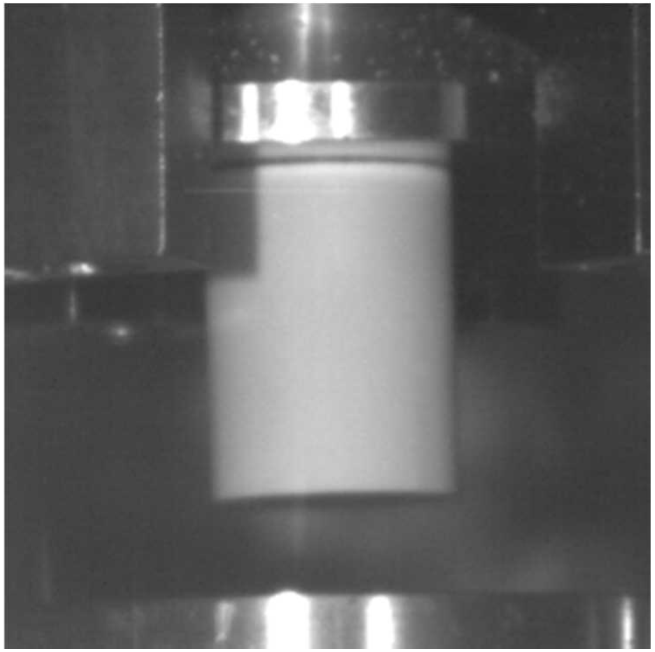
Click to play video

Record: 3700 fps

Playback: 1 fps

RSF200 Compression at Ambient





Click to play video

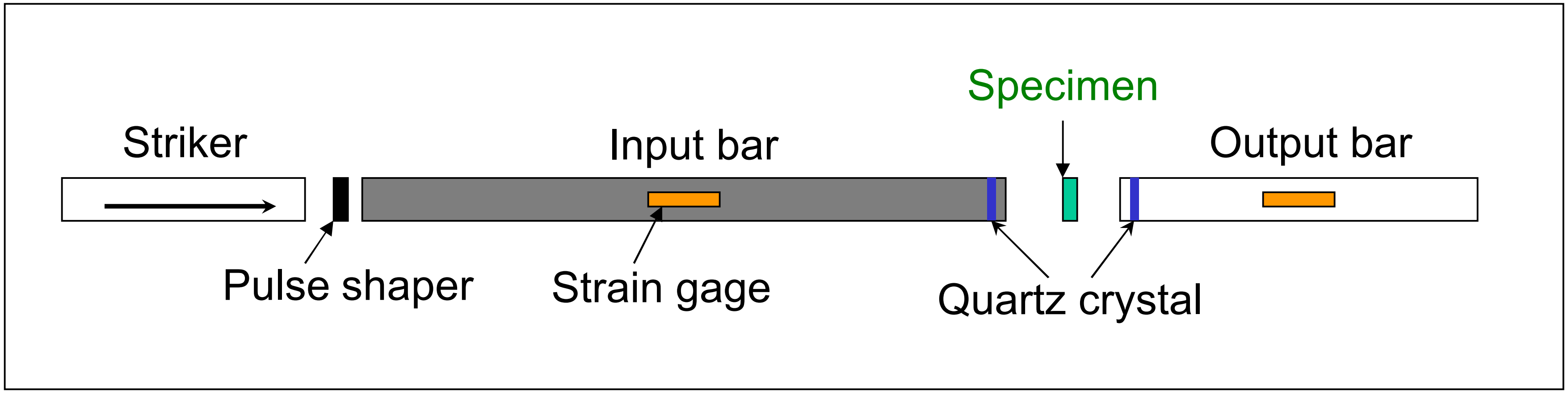
Record: 3700 fps

Playback: 1 fps

High Strain Rate

500 /s < Strain Rate

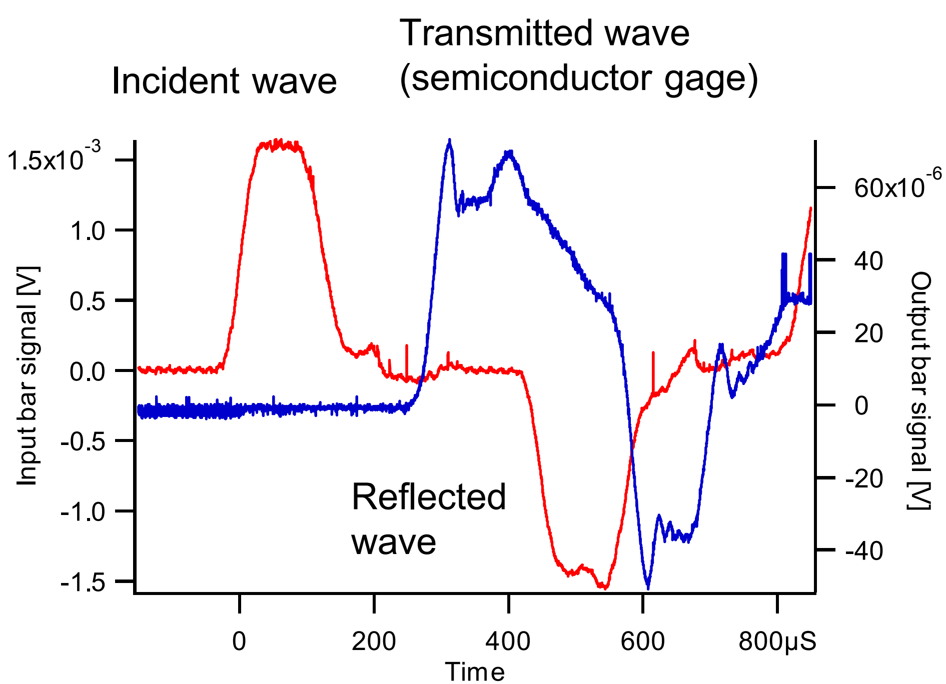
- *Split Hopkinson Pressure Bar (SHPB)*; 7075 Al, 0.75 in diameter
- Two *quartz crystals* to measure force on both sides of the specimen
- Semiconductor strain gages on the output bar



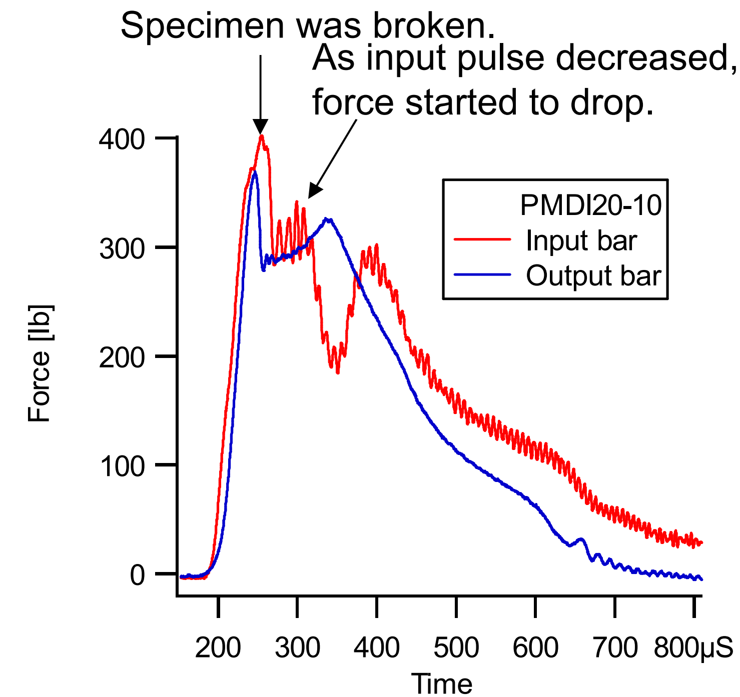
PMDI20 Compression at Ambient

- Strain gage and piezoelectric quartz signals are shown as a representative of typical test result.
- Forces on both side of the specimen were in equilibrium until the specimen started unloading (as input pulse decreased).

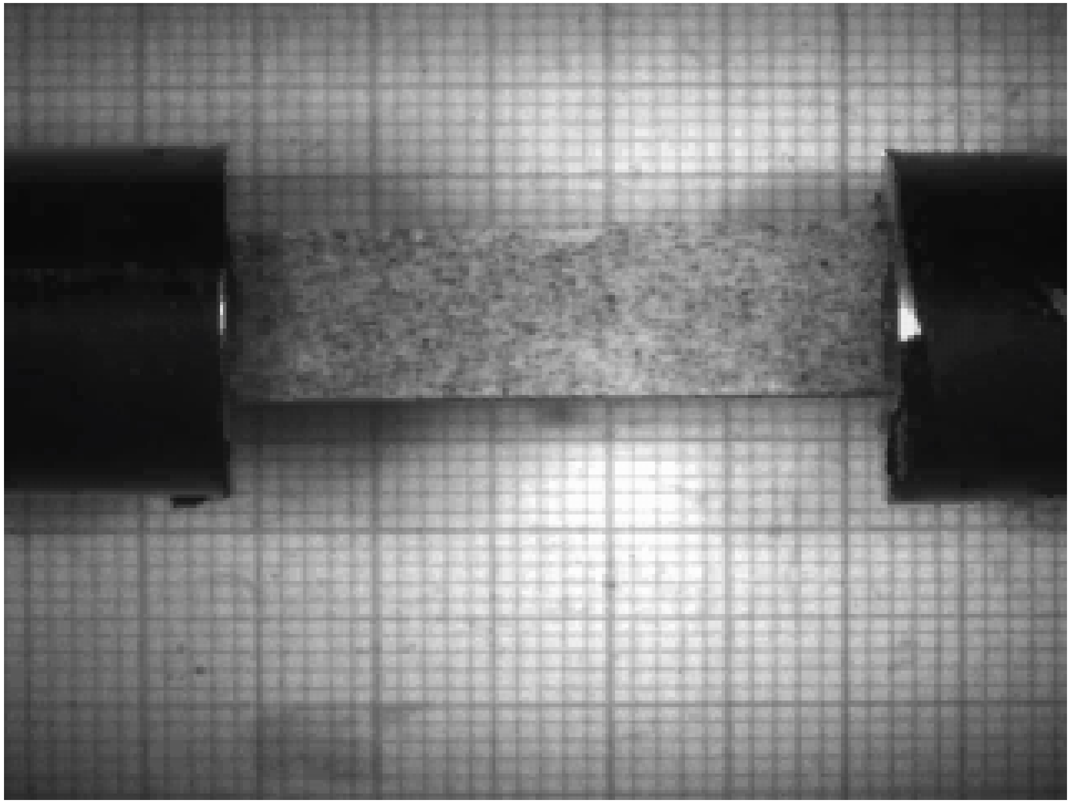
<u>Bar signal</u>



<u>Quartz measurement</u>



PMDI20 High Strain Rate Video



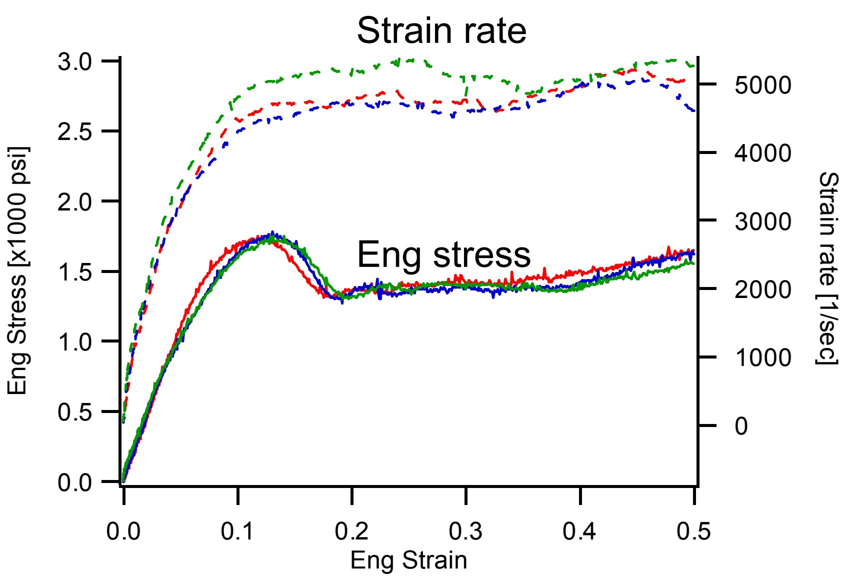
Record: 77,108 fps

Click to play video

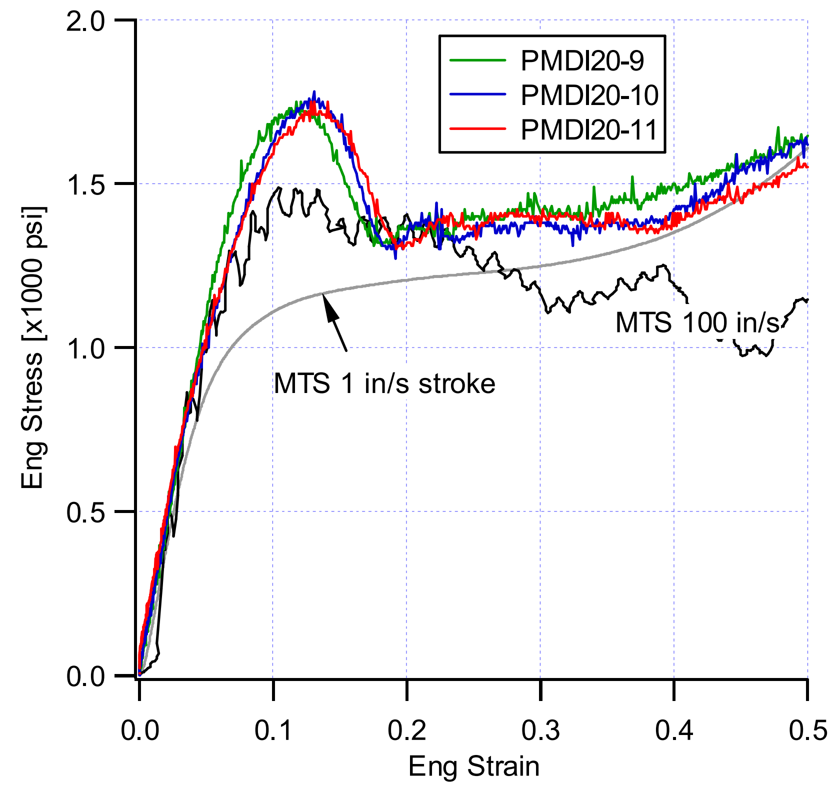
Playback: 5 fps

PMDI20 Results

- Strain rate was about 5000/sec.

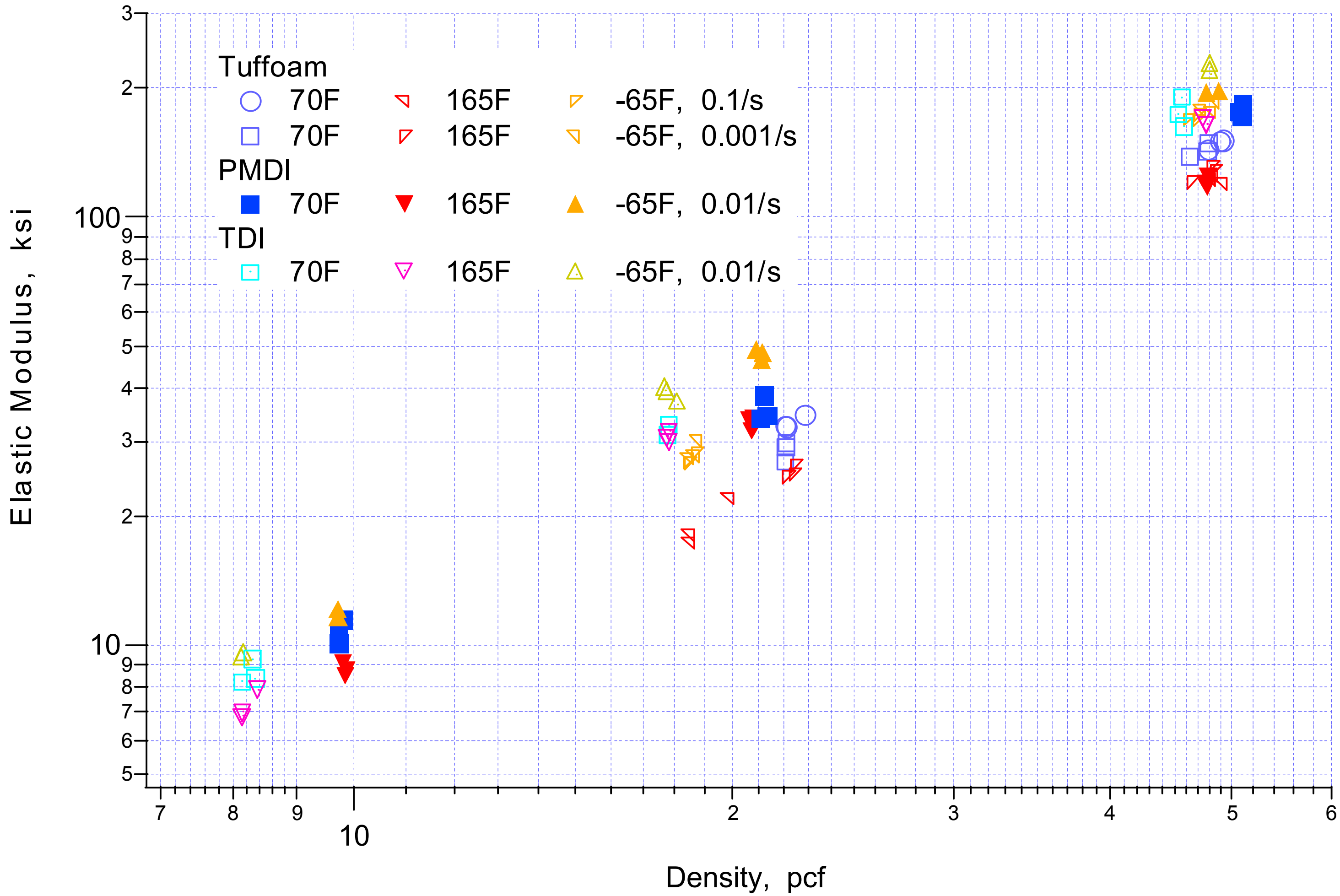


Engineering Stress - Strain



Elastic Modulus vs Density

Polyurethane Foams



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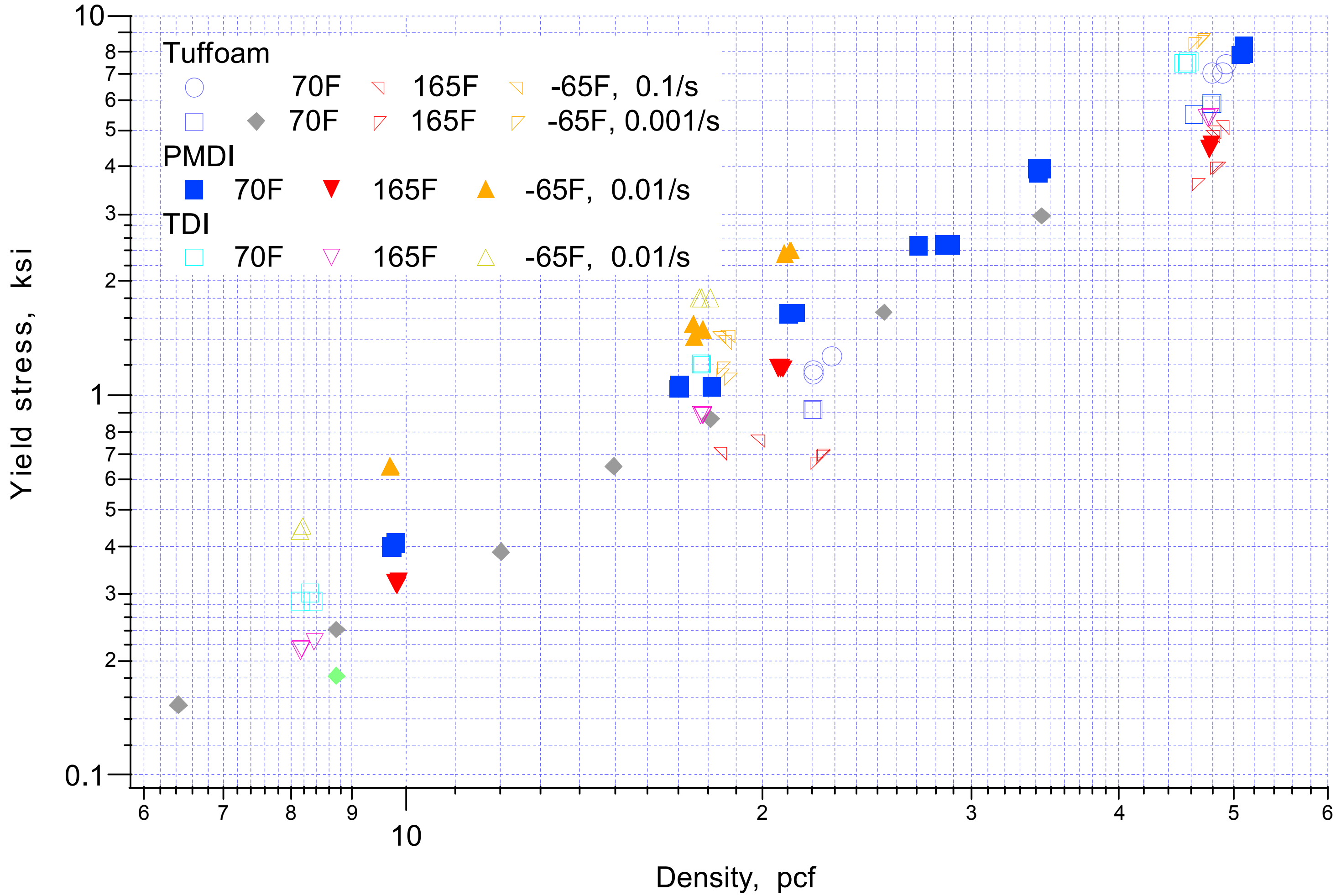
Yield Strength vs Density

Polyurethane Foams



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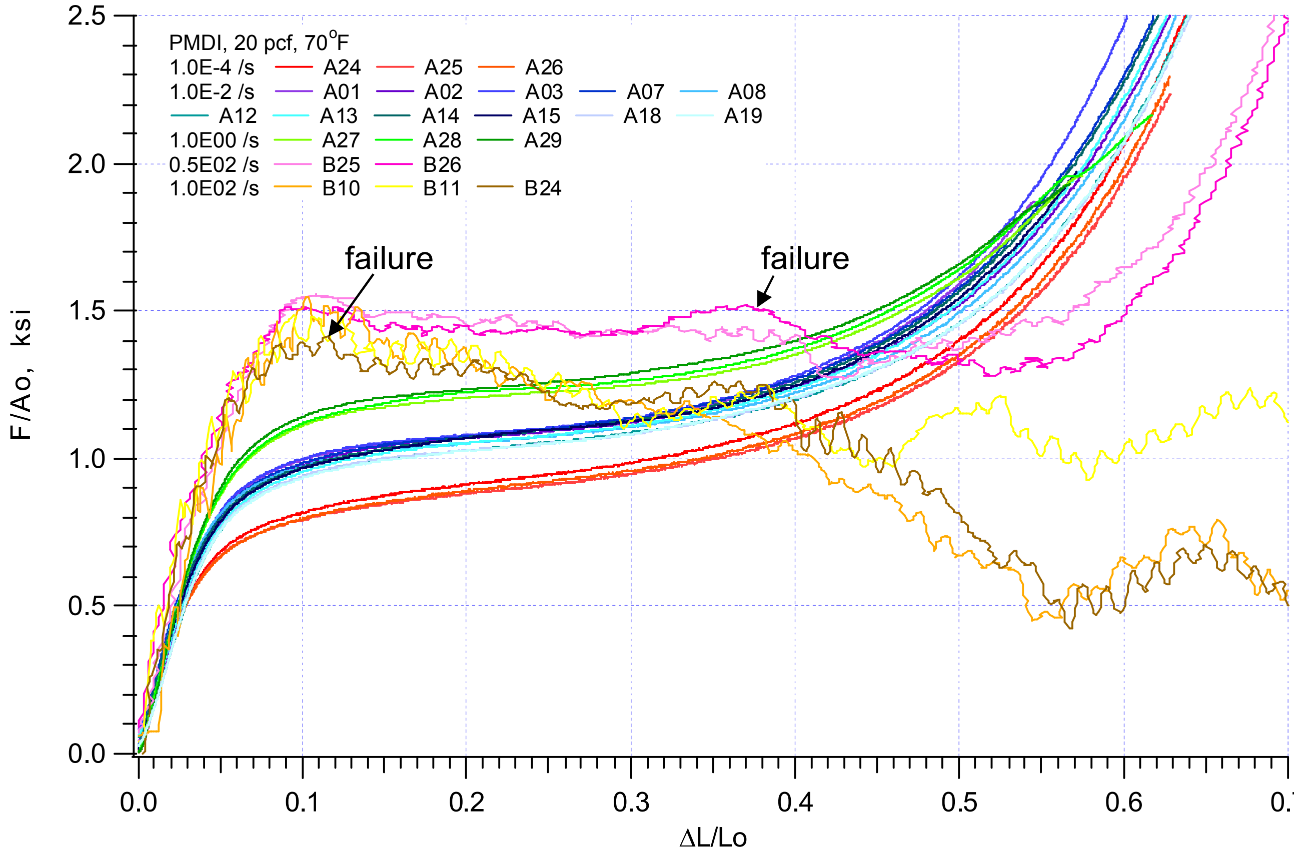
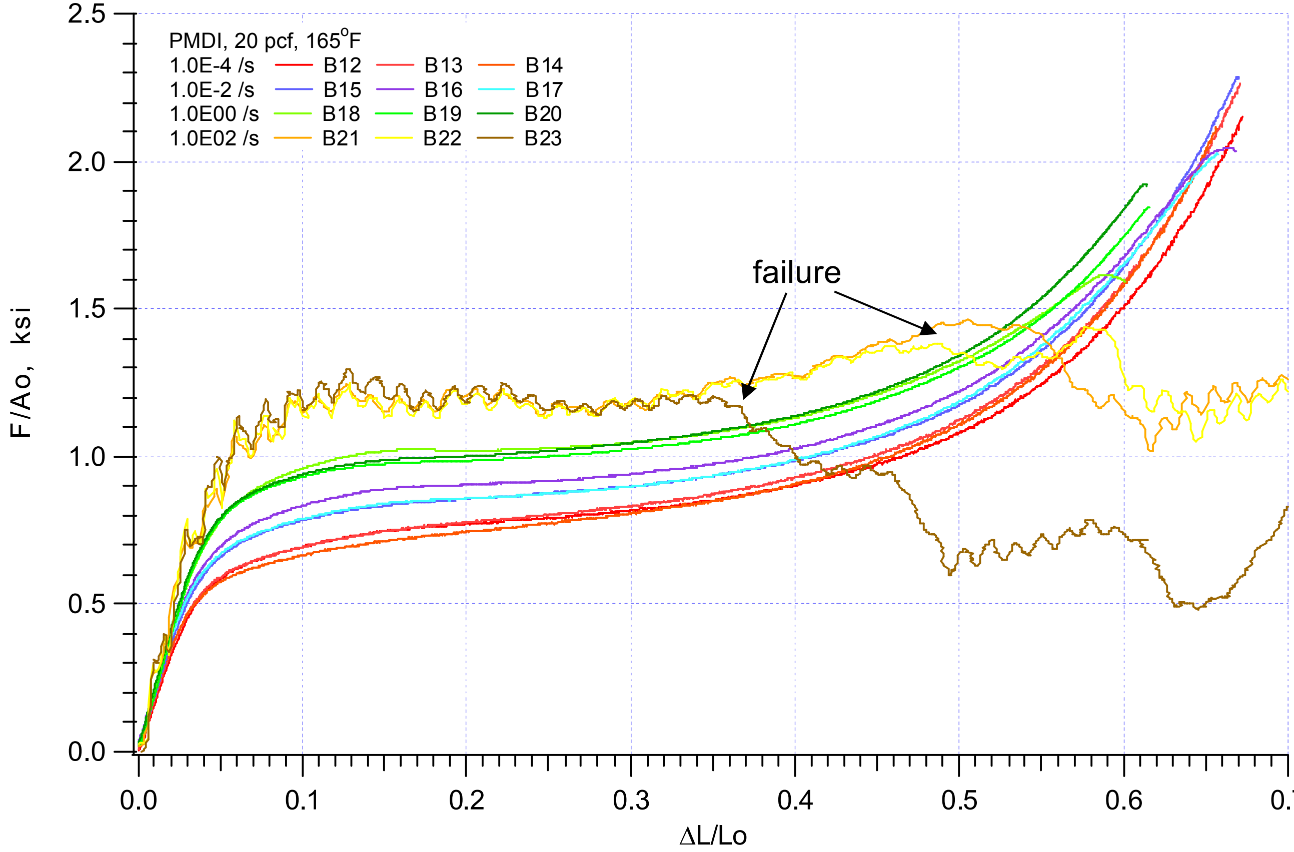
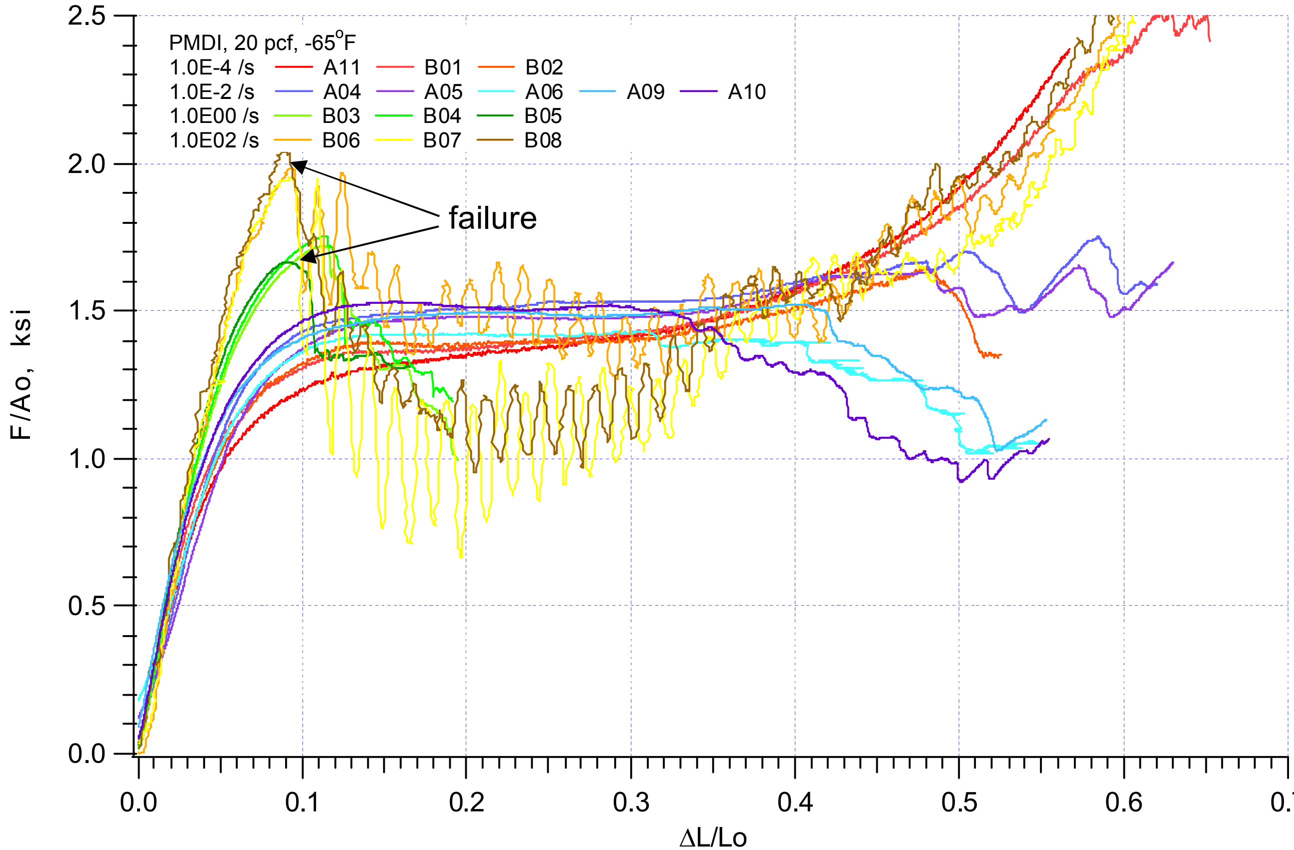
Rate Effect of PMDI 20 pcf at 70°F



Rate Effect of PMDI 20 pcf at 165°F



Rate Effect of PMDI 20 pcf at -65°F

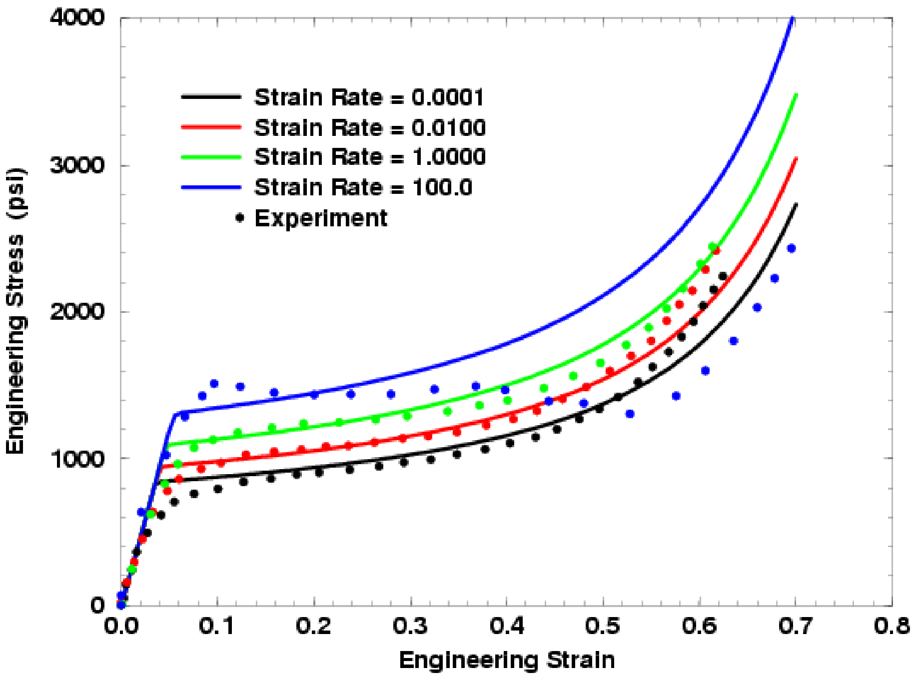


Material Parameters
PMDI foam (17.85 pcf)

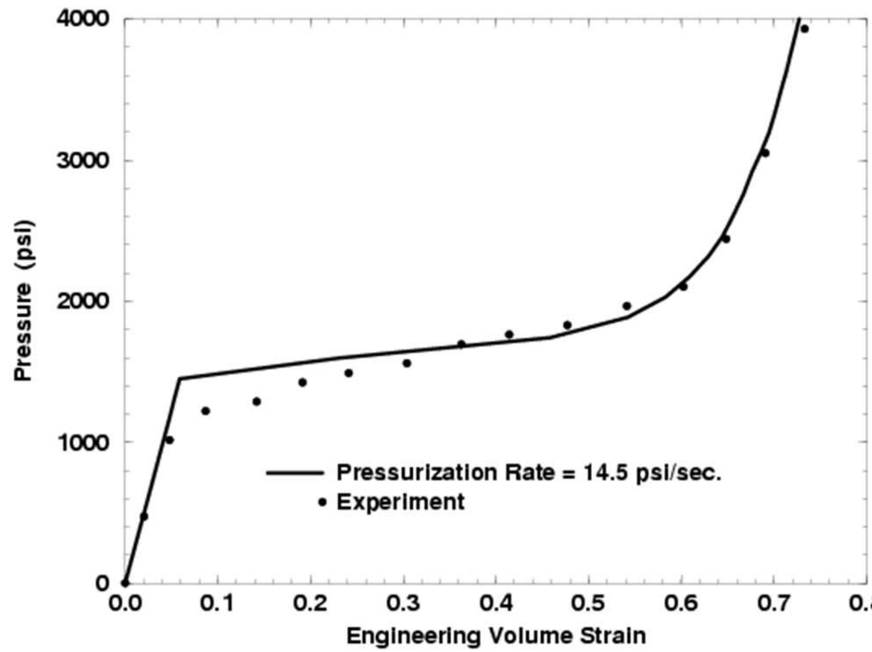
Parameter	Value	Value	Value
Temperature, ^{o}C	-53.0	21.1	73.9
Young's Modulus, psi	27,798	22,600	19,879
Poisson's Ratio		0.343	
Volume Fraction ϕ_o		0.238	
Flow Rate ln(h(θ))	-10.00	2.32	11.00
Power Exponent n(θ)	15.52	13.45	12.00
Shear Strength A_o, psi		513.1	
Shear Hardening A_1, psi		4629	
Shear Exponent A_2		2.9	
Hydro. Strength B_o, psi		971	
Hydro. Hardening B_1, psi		7377	
Hydro. Exponent B_2		4.89	
Beta β		0.95	

Viscoplastic Model fit to PMDI20 Data

- Viscoplastic Foam Model captures deviatoric, volumetric plasticity, and rate effects



Uniaxial Compression at Different Rates
70 F (21.1 C)



Hydrostatic Compression at
Pressurization Rate of 14.5 psi /sec

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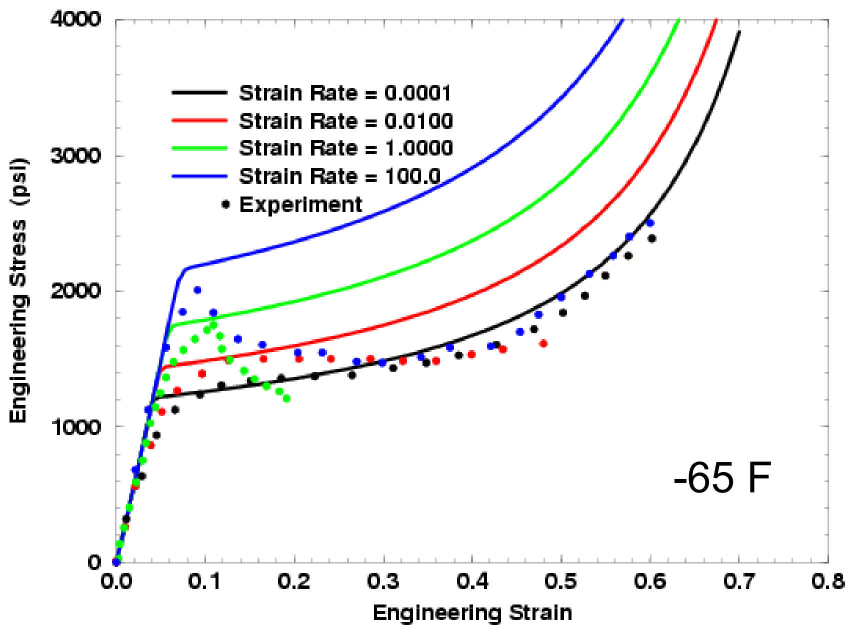
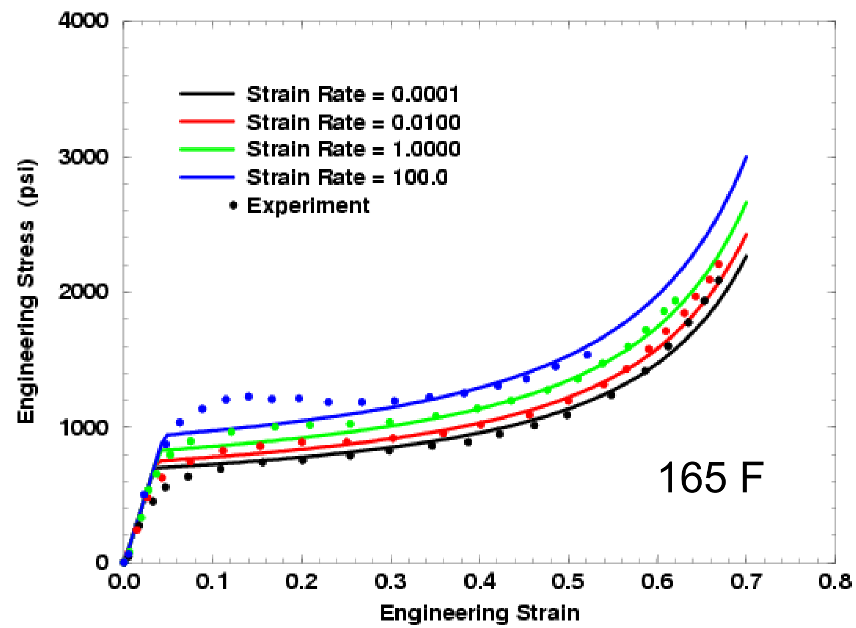
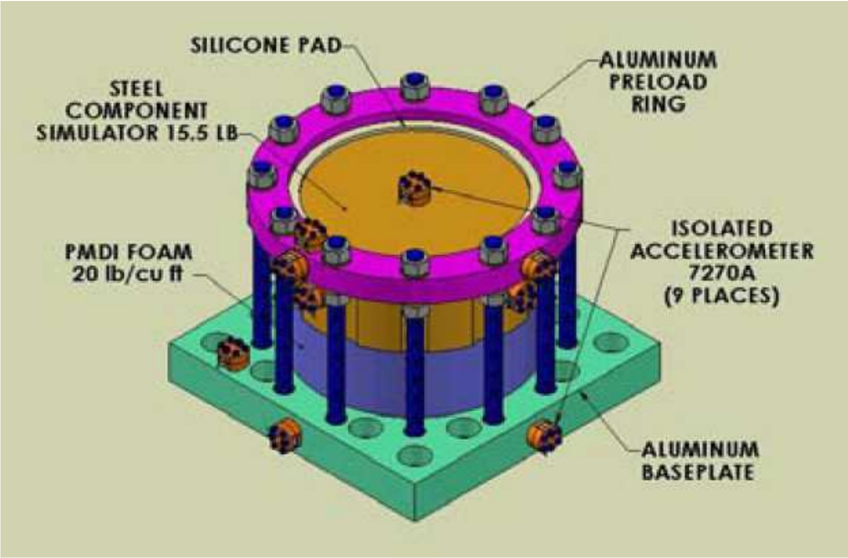
Viscoplastic Model fit to PMDI20 Data

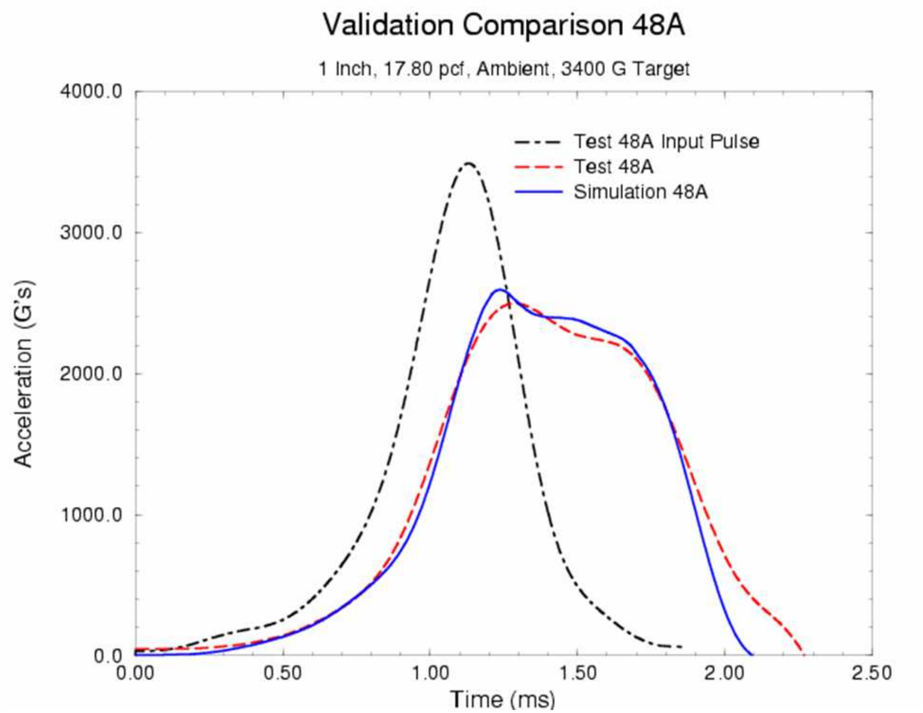
- Viscoplastic Foam Model captures temperature and rate effects.
- Viscoplastic Foam Model does NOT capture foam fracture observed at low temperatures and high rates.





Simulation of Drop Table Test

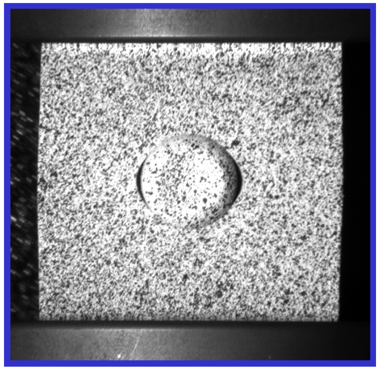


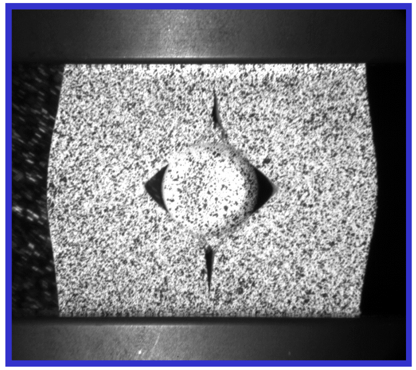


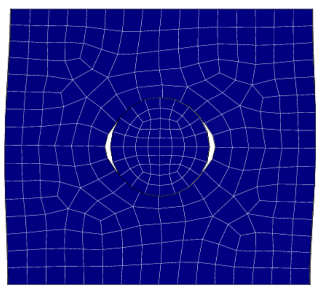
Reference: A. Smith, T. Hinnerichs, C. Lo, M. Neilsen, V. Bateman, L. Carlson, W-Y. Lu, H. Jin, 'Validation of a Viscoplastic Model for Foam Encapsulated Component Response Over a Wide Temperature Range,' presented at IMAC XXV Exposition, Orlando, FL, Febr. 2007

Simulation of Validation Tests

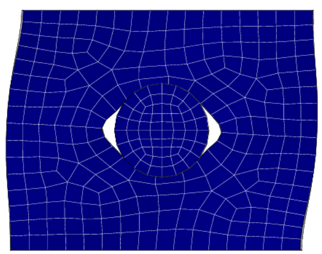
Uniaxial Compression of Foam Block with Steel Rod



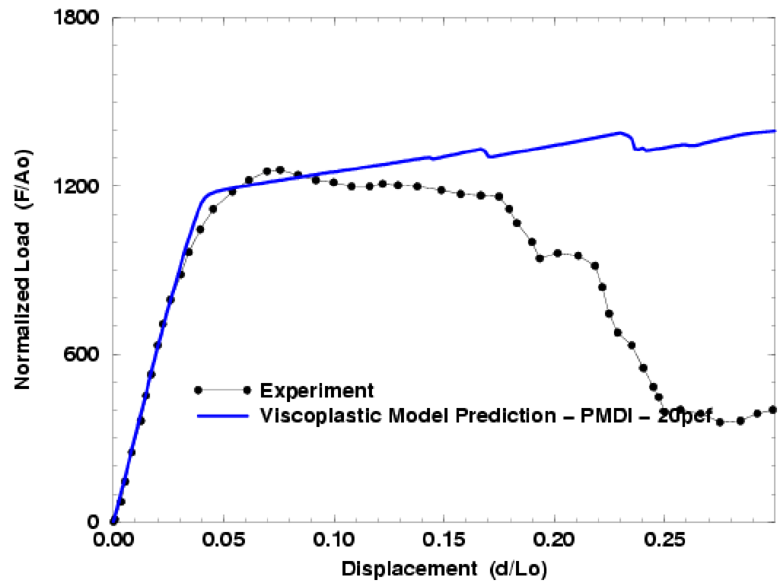




7.5% (Peak load)



15%



Reference: Jin, Helena; Lu, Wei-Yang; Scheffel, Simon; Hinnerichs, Terry D.; Neilsen, Michael K. "Full-field characterization of mechanical behavior of polyurethane foams," International Journal of Solids and Structures; Oct 15 2007; v.44, no.21, p.6930-6944

Summary

- Experiments were conducted on several test frames to fully span the strain rate regime with no gaps: an MTS frame, a high-rate MTS frame, a split Hopkinson pressure bar (SHPB).
- Uniaxial compression stress-strain curves of PMDI20, over wide ranges of temperature (-65 to 165 ^{o}F) and strain rate (10^{-4} to 5,000 s^{-1}), are used to calibrate the viscoplastic foam model.
- Drop and crush experiments are conducted to validate foam models.
- The viscoplastic foam model captures deviatoric and volumetric plasticity as well as temperature and strain-rate effects.
- The viscoplastic foam model does not capture foam fracture.
- Future Work – foam fracture.